THE PROTON SPIN PUZZLE AND
DEPOLARIZATION IN $\bar{p}p \to \bar{\Lambda}\Lambda$

Mary Alberg[a,b,1], John Ellis[c,2] and Dmitri Kharzeev[c,d,3]

[a]) *Department of Physics*
Seattle University
Seattle, WA 98122, USA

[b]) *Department of Physics*
University of Washington
Seattle, WA 98195, USA

[c]) *Theory Division*
CERN
Geneva, Switzerland

[d]) *Physics Department*
University of Bielefeld
33615 Bielefeld, Germany

Abstract

We point out that the measurement of target spin depolarization D_{nn} in the $\bar{p}p \to \bar{\Lambda}\Lambda$ reaction may test dynamical mechanisms invoked to explain the proton spin puzzle revealed by polarized deep–inelastic scattering experiments. In particular, models with *negatively* polarized $\bar{s}s$ pairs in the proton wave function predict $D_{nn} < 0$, whereas models with *positively* polarized gluons would predict $D_{nn} > 0$.

[1]E-mail: alberg@phys.washington.edu
[2]E-mail: johne@cernvm.cern.ch
[3]E-mail: kharzeev@vxcern.cern.ch

The reaction $\bar{p}p \to \bar{\Lambda}\Lambda$ is a testing-ground for different approaches to non-perturbative QCD, in particular the quark model and meson-exchange models. In addition to total cross section and angular distribution measurements at different energies, the spin correlation of the Λ and $\bar{\Lambda}$ have been measured [1]. These were found to be predominantly in a spin-triplet state, with the spin-singlet component very small and consistent with zero within errors. This feature could easily be understood within quark models, if the $\bar{s}s$ pair that carry the $\bar{\Lambda}$ and Λ spins in the naïve constituent quark model were produced by effective vector ($^3S_1$) or scalar ($^3P_0$) field exchange [2]. Spin-triplet dominance could also be accomodated in a meson-exchange model, if the relative phase of the $K-$ and K^*- exchange amplitudes was suitably adjusted [3], but spin-singlet suppression could not be regarded as a natural prediction of this class of models.

There is a plentiful evidence from other experiments at LEAR and elsewhere that baryon wave functions may be more complicated than in the naïve constituent quark model. In particular, the experimental value of the $\pi-$nucleon $\sigma-$term [4] and deep-inelastic experiments [5] provide evidence for hidden $\bar{s}s$ pairs in the nucleon. Most strikingly, several recent LEAR experiments [6] find clear evidence for apparent violations of the OZI quark-line rule in $\bar{p}N \to \phi X$ annihilations, where $X = \gamma, \pi, \pi\pi$. A natural interpretation of these data is in terms of the shake-out or rearrangement of $\bar{s}s$ pairs present in the $\bar{p}N$ initial state [7].

It recently was pointed out [8] that many features of these apparently OZI–violating hadronic processes can be understood if one assumes that the proton wave function contains an admixture of *polarized* $\bar{s}s$ pairs. This assumption is motivated by the experimental results on deep-inelastic scattering [5] which indicate that strange quarks and antiquarks in the proton indeed have a net polarization opposite to the proton spin [9]. An alternative interpretation of these deep-inelastic results ascribes them to to polarized gluons in the proton [10], a suggestion whose implications for low–energy $\bar{p}p$ annihilation have not yet been explored.

The PS185 Collaboration is now proposing [11] an extension of its studies using a polarized target and measuring the depolarization D_{nn} ($p \to \Lambda$ polarization transfer). Quark models generally predict positive values for this quantity [12], whereas meson exchange models generally predict negative values [13]. We argue in this note that these measurements may discriminate between the polarized $\bar{s}s$ and gluon interpretations of the experimental results on polarized deep-inelastic scattering. Specifically, we find that the polarized $\bar{s}s$ model predicts *negative* depolarization $D_{nn} < 0$, whereas the polarized gluon model predicts *positive* depolarization $D_{nn} > 0$. Thus the proposed extension of the PS185 experiment could provide valuable insight into the proton spin puzzle.

The mechanism which is responsible for the negative polarization of the strange sea is most probably of nonperturbative nature. Its origin can be linked to chiral

dynamics [14], and we shall discuss now a particular model based on this idea. We base our discussion on two starting points. First, the fact that the masses of pions and kaons are small at the typical hadronic scale can be attributed to the existence of strong attraction between quarks and antiquarks in the pseudoscalar $J^{PC} = 0^{-+}$ channel. Second, from phenomenological analyses of the strange quark condensate in the framework of the QCD sum rules [15] it is known that the density of strange quark-antiquark pairs in QCD vacuum is quite high [16]: $< 0|\bar{s}s|0 > \simeq (0.8\pm0.1) < 0|\bar{q}q|0 >$. Using the standard value of the light quark condensate [15], $< 0|\bar{q}q|0 > \simeq (250 MeV)^3$, we come to the conclusion that the density of strange quark-antiquark pairs in the vacuum is about 1 fm^{-3}.

Let us now consider the basic $|uud>$ proton state immersed in the QCD vacuum. The strong attraction in the spin-singlet pseudoscalar channel discussed above will induce correlations between light valence quarks from the proton wave function and vacuum strange antiquarks with opposite spins (see Fig.1). As a consequence of this, the spin of the strange antiquarks will be aligned *opposite* to the proton spin. Moreover, we note that in order to preserve the vacuum quantum numbers ($J^{PC} = 0^{++}$), strange quark-antiquark pairs must be in a relative spin-triplet, $L = 1\ {}^3P_0$ state (see Fig.1). Therefore the spin of strange quarks must also be aligned *opposite* to the proton spin. The resulting wave function of the $\bar{s}s$ containing component, consistent with parity and spin constraints, corresponds to a spin-triplet, polarized $S_z = -1\ \bar{s}s$ pair with angular momentum $L_z = +1$ coupled to the "usual" $S_z = 1/2\ |uud>$ state. This wave function is similar to the one used in [8], which makes identical predictions for triplet–dominance and depolarization in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$.

The picture advocated above should be contrasted with a similar but inequivalent one based on effective chiral theories with direct quark–Goldstone couplings [17]:

$$\mathrm{L}_{int} \sim \bar{\Psi}\gamma^\mu\gamma_5\Psi\partial_\mu\varphi, \tag{1}$$

where Ψ is a quark field, and φ is the field of a (pseudoscalar) Goldstone boson. In these theories, a light quark can emit a spin-zero Goldstone boson, and this induces spin-flip of the quark. If the emitted boson is a K-meson, the emission turns the light quark into a strange quark with the opposite spin orientation (see Fig.2a). As before, this leads to the polarization of strange quarks opposite to the spin of the proton. The K-meson can in turn dissociate into a strange antiquark and light quark, which leads to formation of the $|uud\bar{s}s>$ component considered above (see Fig.2b). However the Goldstone fields now are to be treated as elementary, spin-zero fields, and as such they dissociate into an *unpolarized* $(q\bar{s})$ pair. Though the net polarization carried by the $\bar{s}s$ pair is again opposite to the proton spin, the $\bar{s}s$ pair itself can be in either a spin-triplet or spin-singlet state with statistical weights.

We observe that the mechanism responsible for the contribution of the strange sea to the proton spin can be tested in the process of proton–antiproton annihilation

into the hyperon– antihyperon pair, $\bar{p}p \to \bar{\Lambda}\Lambda$. In the model we advocate above, this process can be viewed [8] as the dissociation of a spin-triplet $\bar{s}s$ pair from the initial proton or antiproton into a $\bar{\Lambda}\Lambda$ state (see Fig.3). Since the spin of the Λ is carried by the spin of the strange quark, this (spin correlation conserving) dissociation leads to a spin–triplet final state for the two hyperons[4]. This is indeed consistent with the experimental observation [1] that the spin–singlet fraction in the $\bar{\Lambda}\Lambda$ final state is equal to zero within statistical errors. On the other hand, the effective chiral theory (1) would not lead *a priori* to this conclusion.

However, dominance by the spin–triplet state of $\bar{\Lambda}\Lambda$ is not unique to the "intrinsic strangeness" model. It is also a feature of the naïve quark model approach to this process [2], since in this approach the $\bar{s}s$ pair is produced through the $\bar{q}q \to \bar{s}s$ subprocess mediated either by a gluon exchange or by an effective scalar field; in both cases the structure of the $\bar{s}s$ producing vertex ($^3S_1$ and $^3P_0$ respectively) allows only a spin–triplet $\bar{\Lambda}\Lambda$ final state [2].

There exists, however, a way to test the polarized intrinsic strangeness model in the $\bar{p}p \to \bar{\Lambda}\Lambda$ process. This model predicts more than just the dominance of the spin-triplet state in $\bar{\Lambda}\Lambda$. Since the initial $\bar{s}s$ pair carries a polarization opposite to the (anti)proton spin, it predicts that the spin of the final $S = 1$ $\bar{\Lambda}\Lambda$ pair is polarized in the direction opposite to the spin of initial spin-triplet $\bar{p}p$ state.

An experimental observable [11] which measures the amount of spin transferred from the initial-state proton to the final-state hyperon is the depolarization D_{nn}. Assuming a fully polarized proton target, the depolarization D_{nn} ($\vec{n}$ is normal to the production plane) is +1 if the spin of the final-state Λ hyperon is always parallel to the spin of the target, and -1 if the spin of the Λ is always opposite to the spin direction of the target. The polarized intrinsic strangeness model in the idealized version described above therefore predicts $D_{nn} = -1$.

We contrast this prediction with what we would expect within the polarized gluon interpretation of the proton spin puzzle. According to one favoured formulation of this interpretation [10], the negative experimental value of the axial current matrix element

$$< p|\bar{s}\gamma_\mu\gamma_5 s|p >= \Delta s \; s_\mu, \tag{2}$$

where s_μ is the proton spin vector, is due to the $U(1)$ axial anomaly, which induces a correction:

$$\Delta s = \Delta\hat{s} - \frac{\alpha_s}{2\pi} \Delta G, \tag{3}$$

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[4]Studies of initial– and final–state interactions suggest that these do not affect significantly the simple polarization arguments we present here and elsewhere in this paper. Calculations for several different initial- and final- state interactions show changes in D_{nn} of order 30%, averaged over scattering angle. However, the distinction in sign between the quark models and meson-exchange models persists, i.e. D_{nn} is positive for quark models and negative for meson-exchange models [12],[13].

where $\Delta\hat{s}$ is the polarized $\bar{s}s$ contribution prior to quantum corrections, and ΔG is the net gluon polarization in the proton. In the most absolute version of this interpretation, $\Delta\hat{s}$ could vanish and the *negative* measured value $\Delta s < 0$ could be entirely due to a *positive* value of ΔG. If intrinsic gluons were responsible for $\bar{s}s$ production during the $\bar{p}p$ annihilation via the perturbative vertex

$$Ł_{QCD} \sim \bar{\Psi}\gamma_\mu\Psi \ G^\mu, \tag{4}$$

the $\bar{s}s$ pair would be produced in a spin-triplet state, as inferred from the $\bar{\Lambda}\Lambda$ spin correlations. *However*, if $\Delta G > 0$ as suggested in the gluon interpretation of the proton spin puzzle, the depolarization should be *positive*: $D_{nn} > 0$ (see Fig.4). We note however that the more conventional quark model based on effective vector exchange also predicts positive depolarization [12].

Thus the measurement of the depolarization in the $\bar{\Lambda}\Lambda$ process could serve as an interesting test of the dynamics responsible for the apparently "anomalous" decomposition of the proton spin.

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Figure captions

Fig.1 a,b) Strong correlation between light valence quarks and vacuum strange antiquarks in the spin–singlet pseudoscalar channel induces a spin–triplet $\bar{s}s$ component of the proton wave function aligned opposite to the proton spin. (In all figures the direction of spin quantization is taken normal to the plane of the quark line diagrams.)

Fig.2 a) The emission of a K^+ meson turns the light quark into a strange quark with the opposite spin orientation. b) Dissociation of the K meson leads to formation of an $\bar{s}s$ component with *net* polarization opposite to the proton spin, but the $\bar{s}s$ pair can be in either a spin–triplet or a spin–singlet state with *a priori* statistical weights.

Fig.3 The $\bar{p}p \to \bar{\Lambda}\Lambda$ process viewed as the dissociation of a spin–triplet $\bar{s}s$ pair from the initial state proton (or antiproton) wave function into a $\bar{\Lambda}\Lambda$ state. The spin of the produced Λ is always opposite to the spin of the initial proton.

Fig.4 The $\bar{p}p \to \bar{\Lambda}\Lambda$ process viewed as the dissociation of a polarized gluon from the initial state proton (or antiproton) wave function into a spin–triplet $\bar{s}s$ state. The spin of the produced Λ is parallel to the spin of the gluon, which is in turn parallel to the spin of the initial proton.

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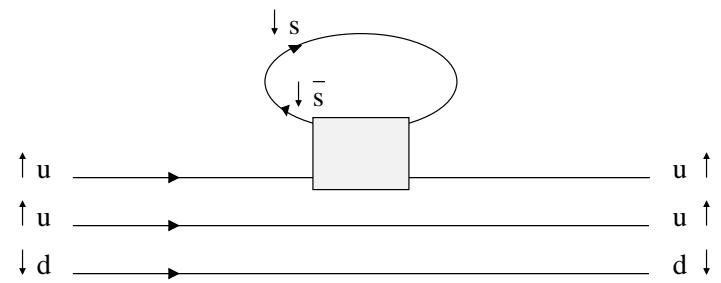
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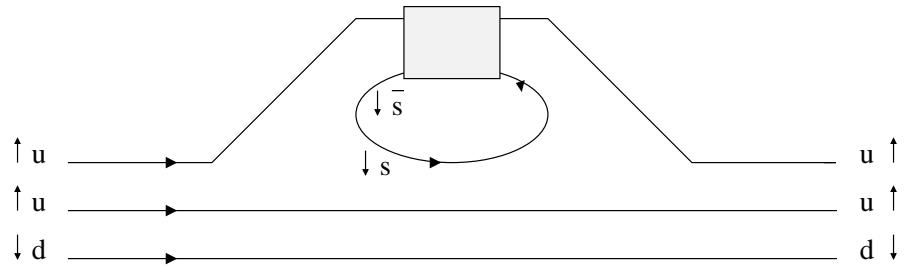
Fig. 1b)

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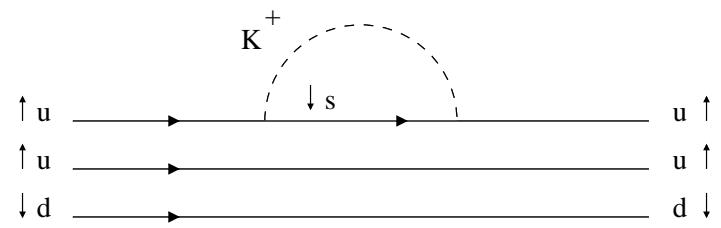
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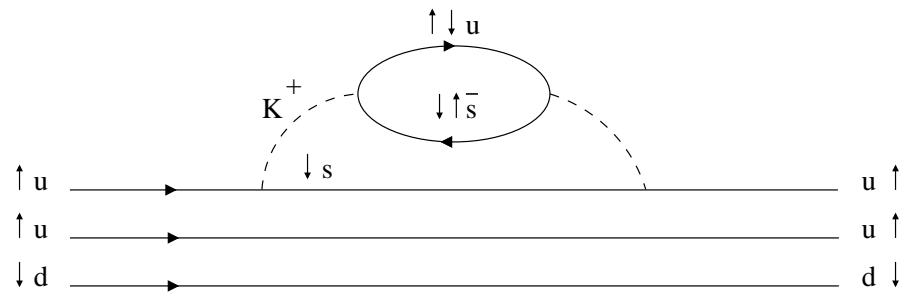
Fig. 2b)

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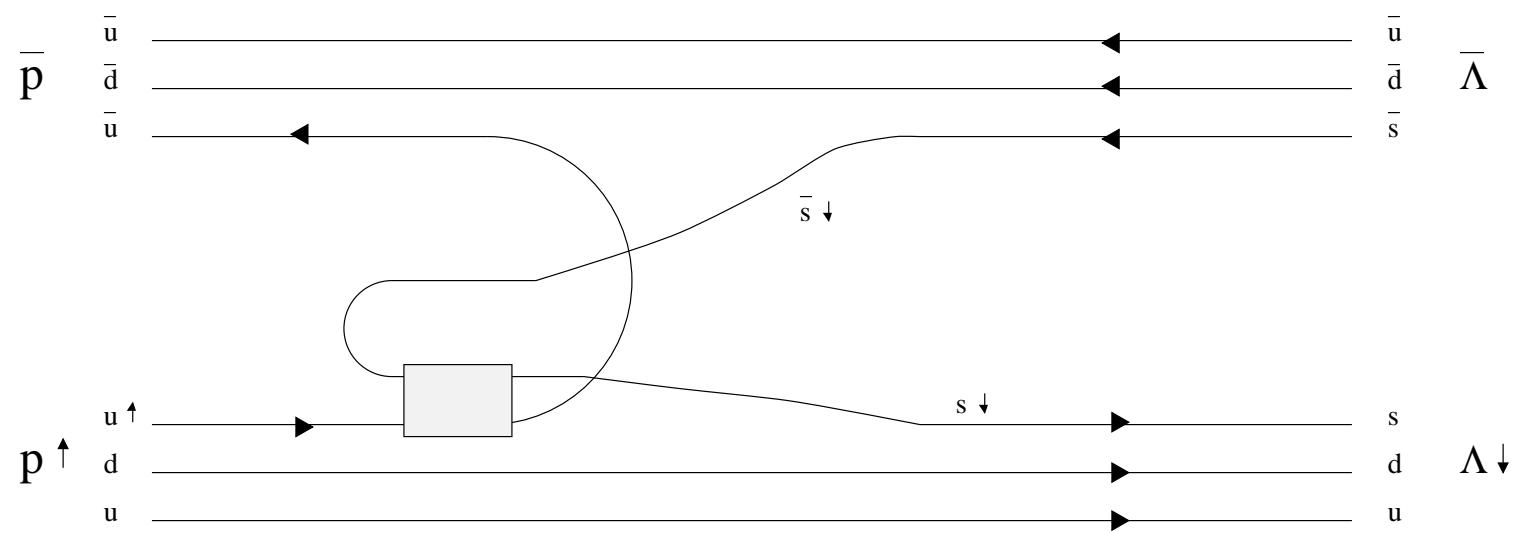
Fig. 3

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Fig. 4